

REHABILITATION IN SPINAL CORD INJURIES



Jacqueline Reznik
Joshua Simmons

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DEDICATION

This book is dedicated with love to my friend and colleague Wilma Anić (nee McPherson), whose love of life and exuberant personality allowed her to conquer all. What I learned from Wilma, in my early years as a physiotherapist at the Spinal Unit at Stoke Mandeville Hospital, allowed me to treat all

my future patients with the care and understanding they needed.

Wilma's addition to the staff of the Physiotherapy Department at SMH by Ida Bromley taught us all the true meaning of rehabilitation.



'Wee Jackie'
Wilma Anić (nee McPherson) MCSP (1943–2019)

PREFACE

HOW THIS BOOK SHOULD BE USED

This book is not intended to be read 'cover to cover', but rather to be used as a handbook that allows easy access to the reader who is searching for specific answers to particular questions regarding the management of their patient(s) with a spinal cord injury (SCI). The book is divided into 21 chapters, beginning with the neuroanatomy and neurophysiology of the spinal cord. It endeavours to tell the story of the total rehabilitation of a patient with a traumatic SCI from the initial injury through to long-term living with the consequential neurological damage. The appendices included allow the reader easy access to commonly used assessments for the spinal cord injured person.

All chapters follow a general theme and have been written by experts in their fields. Some of the chapters are designed to give didactic instructions

on treatments and interventions, others to furnish the treating therapist with new ideas and different approaches, while others are written by people with SCIs and give practical solutions to everyday problems. Each chapter is intended to be succinct and the reader is encouraged to read the Evidence-based practice points at the end of each chapter in order to gain an overview of the key messages associated with the topic. If further information is required, all chapters have a comprehensive bibliography.

The editors would like to note that the words 'patient, client, person/individual with a spinal cord injury' are used interchangeably throughout the text. The term is dependent upon the context in which it is used, for example, the stage of the rehabilitation journey (inpatient vs community) or the intention of the statement (e.g. health professional advice). However, each term is always used with the greatest respect intended.

FOREWORD

It gives me great pleasure to write a foreword for this book, which fills a need for a practical guide to the management of spinal cord injury (SCI). For centuries, this condition was considered 'an ailment not to be treated',¹ since it resulted in certain death. However, since the introduction of comprehensive care for people with SCI after World War II, and improvements in pre-hospital management and medical care, survivors now have a normal lifespan, and can expect to live a productive life.

While there is considerable international effort directed at new treatments for repair of the injured spinal cord, there has also been a transformation in the management of SCI. This book tracks the patient journey from pre-hospital and acute hospital management through to rehabilitation, and goes beyond hospital care to living in the community, including ageing with an SCI. Edited by two physiotherapists with substantial clinical experience in the field of spinal cord injury, this book includes contributions by an anatomist, a paramedic, medical practitioners, physiotherapists, occupational therapists and psychologists. Chapters on biomechanics, paediatric SCI, high cervical injuries and the tetraplegic upper limb are not typically addressed in other texts on this subject. The chapter on biomechanics provides an analysis of the biomechanical principles involved in basic tasks, such as bed mobility, sitting balance, transfers and pushing a wheelchair. One standout feature of the book is that three chapters have been written by people with lived experience of SCI, offering

their welcome perspective on exercise and sport, sociological issues and the hazards of living with an SCI.

The material in this book is practical, each chapter including practice points, and it would be particularly useful for undergraduates and new graduates. However, more experienced graduates in medical and allied health disciplines may find this book helpful in refreshing or increasing their knowledge.

There will always be improvements in management strategies in the future, as well as advances in our understanding of the nature and consequences of SCI. However, this book provides new and important insights into current aspects of management of SCI, and can be highly recommended.

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ENDORSEMENT BY IDA BROMLEY FCSP

Congratulations to Jackie, my friend and colleague for many years for this interesting and informative book. All who work in this field of rehabilitation know that it is the patients who demolish their boundaries. We simply pass the information to the next generation.

Reference

1. Hughes, J.T., 1988. The Edwin Smith Papyrus; an analysis of the first case reports of spinal cord injuries. *Paraplegia* 26, 71–82.

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Joshua (Josh) Simmons has been a physiotherapist for 20 years and has spent most of his professional life specialising in the management of spinal cord

injury. He has worked across the continuum of SCI management, including acute management post-injury, facilitating transition back to the community and long-term follow-up. He was the Clinical Team Leader at the Spinal Injury Unit at Princess Alexandra Hospital as part of the Queensland Spinal Cord Injury Service (QSCIS) from 2005 to 2019.

Josh has served as an Executive Member of the Australia and New Zealand Spinal Cord Society (ANZSCoS), including roles as Secretary and Vice President. He is a member of the Australian and International Physiotherapy Networks and regularly lectures to undergraduate university students on the topic of SCI management.

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CHAPTER 1

Introduction to spinal cord injury

Helen Ancomb

1. OVERVIEW OF THE ANATOMY AND PHYSIOLOGY OF THE SPINAL CORD

INTRODUCTION AND OVERVIEW

The spinal cord is a component of the human central nervous system (CNS), which includes the brain and spinal cord. The brain is complex and has many diverse functions, such as consciousness, thought, imagination, creativity, attention, executive functions, language, emotional experience, learning and memory. Additionally, it modulates and regulates the functions of the organ systems, the endocrine system and motor control.

The spinal cord is, in many ways, a more straightforward part of the CNS. The structure of the spinal cord is much simpler, and it displays a uniform organisation throughout its length. The processing within the spinal cord, however, is complex and it serves extremely important functions: it receives much of the sensory information we have about the world around us, carries all of the motor information that supplies our voluntary muscles and it serves as

a conduit for the longitudinal flow of information to and from the brain.

Sensory receptors outside of the CNS act as transducers that change in response to physical and chemical stimuli in our internal and external environments. These stimuli produce nerve impulses that are sent directly to the spinal cord, which performs the initial processing of inputs. These sensations are then sent to the brain, which can interpret our sensations and provide us with meaning. Some of this input directs the voluntary control of our body movements, the signals for which come directly from the neurons of the spinal cord.

DEVELOPMENT FROM THE NERVOUS SYSTEM

A brief overview of the development of the nervous system and an understanding of these processes aids

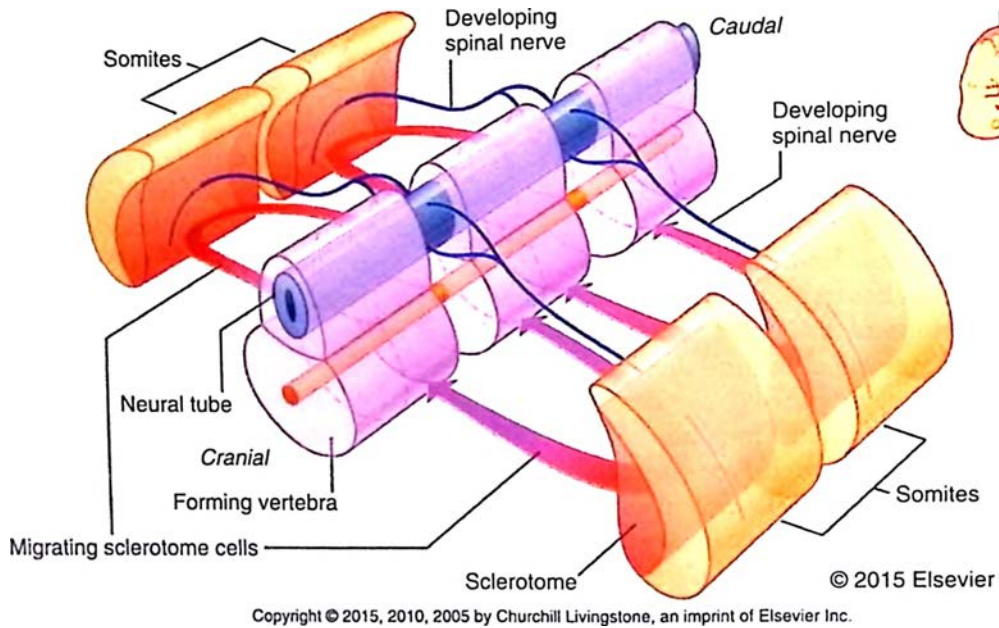


Figure 1.1 Developing spinal cord.

The developing spinal cord/neural tube (derived from endoderm) and somites (derived from mesoderm). This image illustrates the relationship between the developing spinal cord, the spinal nerves and the somites.

Source: Drake, R., Vogl, W., et al., 2014. Gray's anatomy for students, 3rd edn. Elsevier.

in understanding the adult structure and organisation of the spinal cord (Fig. 1.1).

In early embryo development, three germ layers are formed which subsequently give rise to the tissues and structures of the human body. These are: the ectoderm, endoderm and mesoderm. The ectoderm gives rise to the nervous system (and epidermis of the skin) and these tissues become integrated early in life with the other germ layers and their structures. The endoderm develops into the internal organs (viscera) of the body and the mesoderm gives rise to somites. Somites are segmental structures that develop into bone, skeletal muscle and the dermis of the skin (from which many receptors for sensations are developed).

Innervation to the structures derived from somites is through the somatic division of the nervous system, while the innervation of the structures derived from the endoderm is through the visceral part of the nervous system (Fig. 1.2).

The early development of the nervous system originates from a simple tube of ectodermal tissue, termed the neural tube. This begins through a process termed neurulation that occurs at around the third week of gestation. Neurulation commences through the thickening of a longitudinally oriented (from rostral to caudal) band of ectodermal tissue. This thickening is the neural plate, which develops due to the presence of the notochord, a rod-like structure that lies beneath the neural plate. The notochord is an important primary inductor in the early embryo, which is known to initiate and control the process of neural tube development and which, if damaged, can lead to spinal cord and CNS defects (such as spina bifida).

Following development of the initial neural plate, a midline groove appears on the plate and the plate folds inwards, creating a deepening groove with neural folds at the outer edges. This folding continues until the neural folds meet in the midline

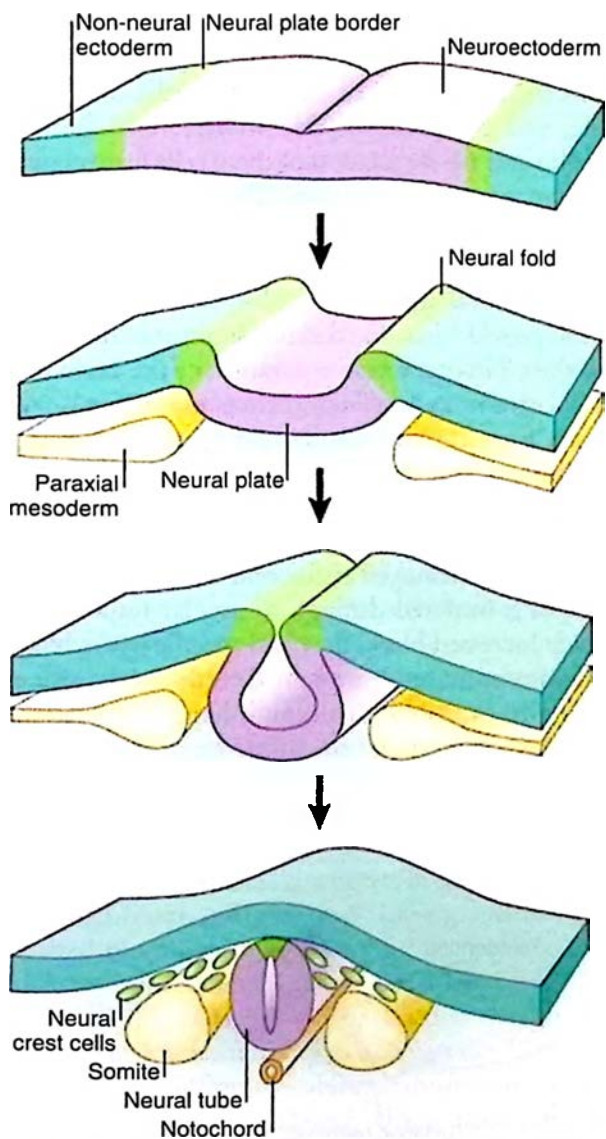


Figure 1.2 The development of the neural tube from endoderm.

The formation of the neural plate (under the influence of the notochord), and folding of the plate to create the neural tube, sitting beside paraxial mesoderm that forms the somites.

Source: Gammill, L.S., Bronner-Fraser, M., 2003. Neural crest specification: migrating into genomics. *Nature Reviews Neuroscience* 4, 795–805.

and fuse to create a hollow neural tube towards the end of the third week. The rostral end of the neural tube undergoes a complex and expansive process of development to form the human brain, while the remaining neural tube develops into the spinal cord. The neural tube becomes isolated from the other developing tissues of the human embryo in early development, following closure of the neural pores at either end, to allow the developing neurons of the nervous system to form complex and diverse connections and protecting and isolating them from damage.

THE BLOOD-SPINAL CORD BARRIER (BSCB)

Capillaries in the CNS have a unique structure, being formed by a continuous layer of non-fenestrated endothelial cells linked by tight junctions that have extensive contacts with pericytes, astrocytes, microglia and neurons.¹ Unlike the blood vessels in other organs, CNS blood vessels do not allow the passive leakage of plasma proteins or the entry of immune cells from the blood into the nervous tissue, a structural feature commonly referred to as the blood–brain barrier (BBB), which also exists in the spinal cord. The maintenance of a functional blood–spinal cord barrier (BSCB) is essential to the regulation of the microenvironment in the nervous tissues of the CNS and prevents the exposure of neurons to potentially toxic blood-borne molecules such as fibrinogen and haemoglobin.²

The vitally important homeostatic and protective functions of the BSCB in keeping toxic metabolites, peripheral immune cells and other inflammatory substances excluded from the CNS are demonstrated following traumatic injury to the spinal cord. Upon injury, this protective barrier is completely disrupted, the cell membrane and glycocalyx of endothelial cells is damaged and the tight junctions between cells are lost. This leads to the breakdown of the BSCB, widespread vascular permeability and an inflammatory response.³ It is now understood that BSCB breakdown and inflammation

are both widespread in neurological diseases and are hallmarks of conditions such as stroke,⁴ epilepsy⁵ and multiple sclerosis.⁶ This demonstrates the importance of the BSCB in maintaining the CNS microenvironment for normal physiological processing.

CELLS OF THE CNS AND SPINAL CORD

Neurons

Neurons are the excitable cells of the nervous system and are located both centrally and peripherally. A wide variation in neuronal structure (morphology) is found in the CNS and spinal cord, allowing specificity to function (i.e. sensory neurons are structured differently to motor neurons); however, the basic components of all neurons include a cell body (soma), dendrites, an axon and a synaptic terminal (Fig. 1.3).

Glial cells

Glia were regarded for some time as 'extra' or additional cellular components of the nervous system, whose presence was predominantly related

to providing structural support or scaffolding for neurons. This view can be understood when considering the role of some glial cells (Schwann cells and oligodendrocytes) in the formation of myelin and the association of these cells in structural support of axonal processes. The functions of glial cells in the nervous system are now recognised as being significant for normal functioning, and not just structural support. In addition, the glial cells act to provide first-line defence (immune functions) for the CNS due to the separation of the brain and spinal cord from the systemic circulation. This barrier limits the effects of the systemic immune system on injured and damaged regions of the CNS. In other tissues, following damage and injury to cells, a localised inflammatory response is initiated that will remove damaged tissue and begin repair. This process is initiated through a vascular response, in which increased blood flow and specific white blood cells (immune cells) are sent directly to the site of injury. In the CNS, this cannot happen due to the BSCB. Instead, under the influence of the systemic circulation (and blood-based signalling molecules, such as cytokines), the glial cells of the CNS are

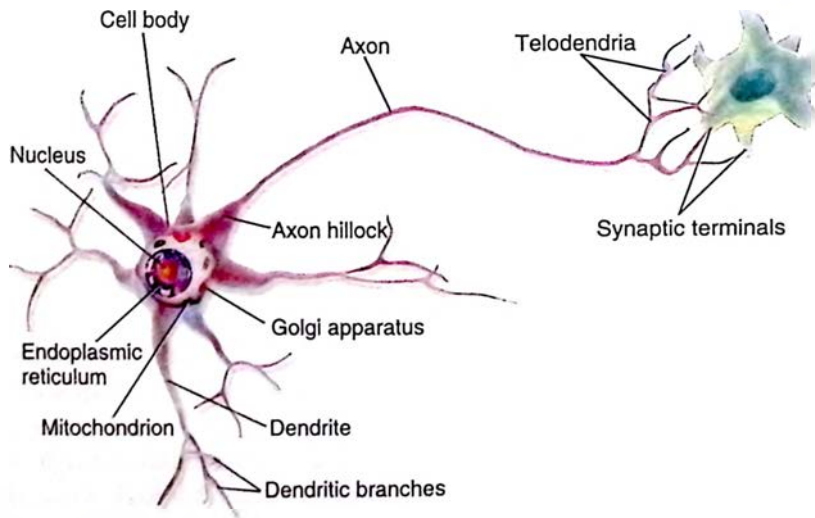


Figure 1.3 The structure of a neuron.

Source: Bruce Blaus C.C. BY 3.0

activated to perform immune-like functions such as phagocytosis.

The 3-part (tripartite) synapse

The term 'tripartite synapse' refers to the theory that synaptic physiology and cellular communication at synapses are dependent upon the activity of three components: the presynaptic neuron, the post-synaptic neuron and an astrocyte.⁷ This concept of glial cells playing an active role in synaptic functions, by responding to and regulating synaptic activity,⁸ was first proposed due to the observation of bi-directional communication between astrocytes and neurons at the synapse.^{9,10} The study of neuron–glial interactions (especially astrocytes) is a rapidly expanding field that challenges the traditional understanding of nervous system physiology, that CNS function results exclusively from neuronal activity/excitability.

An understanding that astrocytes function to assist synaptic physiology is important, given the involvement of glial cells in the inflammatory and repair processes that follow CNS injury. It is most likely that altered and maladaptive functioning within the CNS following injury is the result of altered activity in the neuron–glia network that impacts on both neuronal and glial functioning and disrupts normal physiological processing.

Astrocytes were once considered to be non-excitabile cells due to the fact that they do not show electrical excitability as neurons do. However, it has now been firmly established through numerous studies performed in cultured cells, isolated cells and through *in vivo* studies,¹¹ that astrocytes do exhibit excitability. Unlike neurons, astrocyte excitability occurs through elevated levels of calcium ions (Ca^{2+}) in the cytoplasm. This elevated Ca^{2+} is able to act as a cellular signal.¹² The Ca^{2+} elevations of astrocytes can occur both spontaneously and in response to neurotransmission.¹³

Importantly, the Ca^{2+} responses observed in astrocytes are not simply the result of an excess or overspill of neurotransmitter release at the synapse. Indeed, astrocytes have been shown to selectively

respond to different neurotransmitters (i.e. glutamate and acetylcholine [ACh]), and they are even able to discriminate between different pathways that use the same neurotransmitter. When the astrocytic Ca^{2+} signals produced by different synaptic terminals are analysed in detail, there is evidence that astrocytes are able to integrate synaptic information in the same way neurons do.¹³ In summary, there is clear evidence to support the idea that astrocytes are active cellular processors of synaptic information and contribute an important role to the functioning of the synapse (Fig. 1.4).⁷

Astrocytes (or astroglia) are star-shaped glial cells which are now considered to be active players in CNS

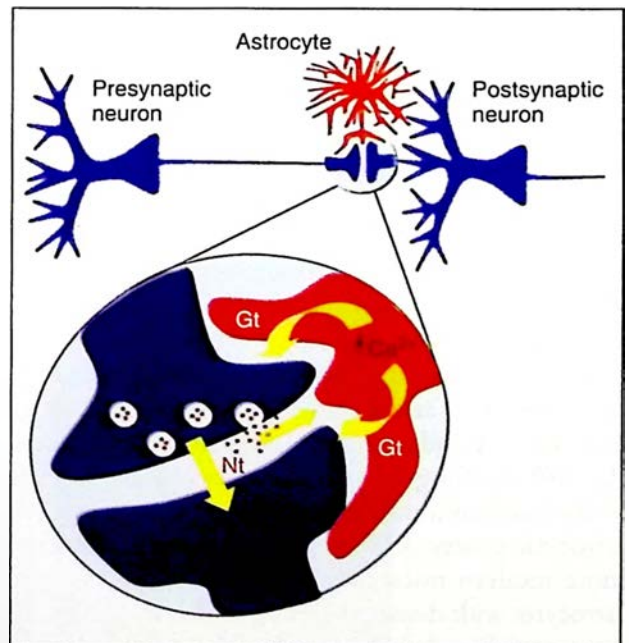


Figure 1.4 The tripartite synapse.

Scheme of the tripartite synapse. Cartoon representing the transfer of information between neuronal elements and astrocyte at the tripartite synapse. Astrocytes respond with Ca^{2+} elevations to neurotransmitters (Nt) released during synaptic activity and, in turn, control neuronal excitability and synaptic transmission through the Ca^{2+} -dependent release of gliotransmitters (Gt).

Source: Perea, G., Navarrete, M., et al., 2009. Tripartite synapses: astrocytes process and control synaptic information. *Trends in Neuroscience* 32:421–431.

function. They contribute to the maintenance of the BSCB, undertake multiple homeostatic mechanisms (mainly relating to neurotransmitter and ion levels) and support synaptic physiology.

There are two major types of astrocytes: fibrous astrocytes, which are found in white matter, and proteoplasmic astrocytes, which are located in the central grey matter of the spinal cord. An additional third type of astrocyte is the Müller cell, found in the retina of the eye. The astrocyte's main function is to support and nurture neurons. They do this through a variety of activities. In the grey matter they take up and recycle excess neurotransmitters from the synapse and maintain ion homeostasis around the neuron to help regulate excitability. In the white matter, their star-like projections form end-feet that line the blood vessels supplying the spinal cord. In this way they form an important component of the BSCB, helping to separate the systemic circulation from direct contact with nervous tissue. Here they play a vital role in maintaining homeostasis by shuttling excess ions into the blood stream. Lastly, they have an active role in signalling and signal modification at the synapse (the tripartite synapse – see Fig. 1.4) through the release of 'gliotransmitters' (i.e. ATP, glutamate, serine).

The largest astrocytes have been shown to have processes that are up to 1 mm in length. It is believed that traditional glial fibrillary acidic protein (GFAP) labelling is only able to reveal about 15% of the total volume of these cells, with most of the astrocytic processes being GFAP-negative. However, more modern microscopy techniques demonstrate astrocytes with dense arborising networks of star-like processes. Fig. 1.5 demonstrates the full astrocyte structure with GFAP labelling. Astrocytes in human parietal cortex are identified in the image using GFAP labelling.¹⁴

Oligodendrocytes

Oligodendrocytes have multiple branching processes that wrap around axons to provide an insulating and protective layer of myelin within the CNS. One oligodendrocyte can myelinate multiple axons,

and axons are myelinated by numerous consecutive oligodendrocytes, each forming a segment of the myelin sheath. As such, oligodendrocytes are present in enormous numbers within the CNS, far exceeding those of astrocytes. Gaps in the myelin sheath, called nodes of Ranvier, occur at regular intervals to allow saltatory propagation of action potentials for neural transmission (Fig. 1.6).

Microglia

Microglia are the smallest of the glial cells and are the immune cells resident within the CNS, having derived from the monocyte–macrophage cell lineage in development. These cells act as specialised phagocytes removing cellular debris and damaged cells. Due to being immune cells they are activated through the release of inflammatory molecules such as cytokines (pro-inflammatory cell signals) and become recruited to areas of neuronal damage. In addition to responding to inflammatory signals, they can function as immune effector cells, secreting cytokines themselves, contributing to the inflammatory cascade and even impacting on neuronal function.

Ependymal cells

The fourth type of CNS glial cell is the ependymal cell, a type of epithelial cell that lines the ventricles of the brain and the central canal of the spinal cord. They separate the cerebrospinal fluid (CSF) from the nervous tissue and function as part of the choroid plexus (along with the pia mater), which secretes the CSF.

SPINAL CORD STRUCTURE

The spinal cord sits within the intervertebral canal of the bony spinal column. It is a long, cylindrical and segmented structure with a consistent organisation throughout its course. It is a direct continuation of the brainstem and does not descend lower than the lumbar vertebrae in the adult. It receives sensory inputs from the limbs, trunk and many internal organs, and contains the somatic motor tracts that

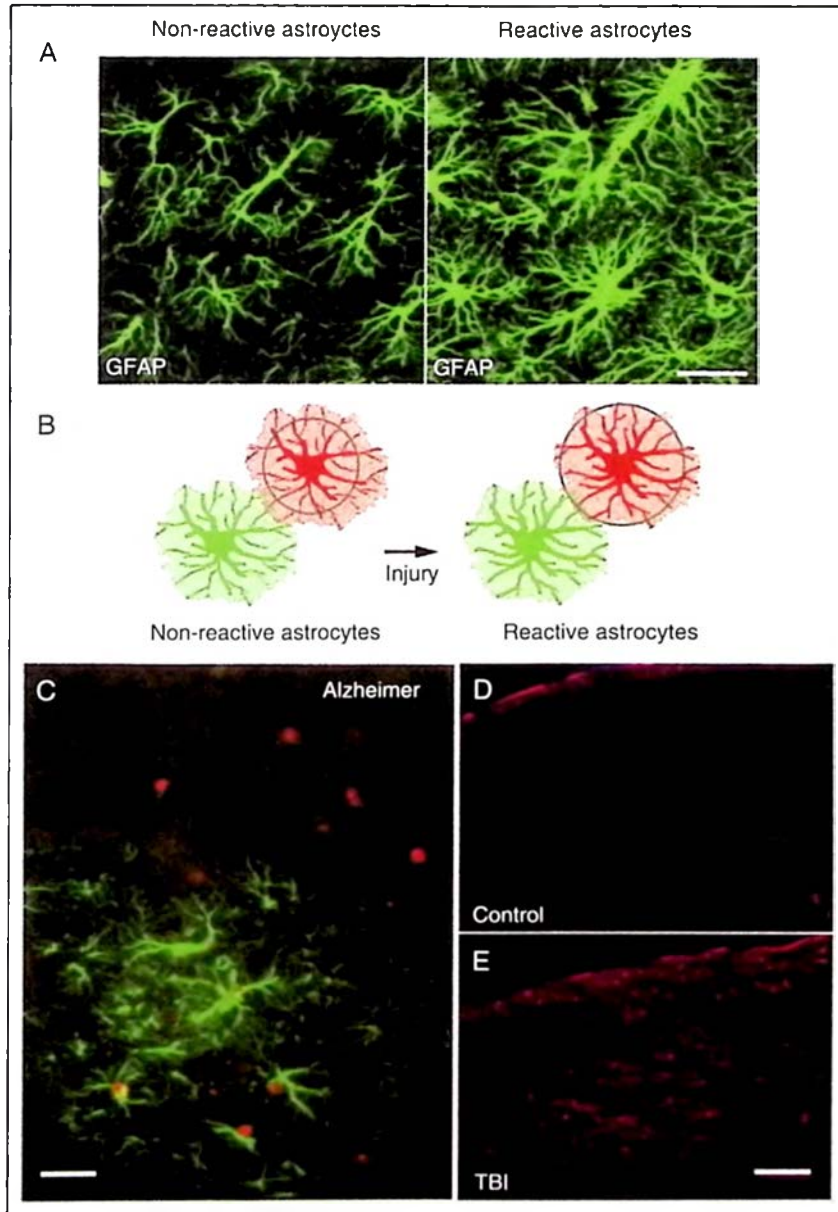


Figure 1.5 Reactive astrocytes show an upregulation of the IF protein GFAP and hypertrophy of cellular processes, but stay within their tiled domains.

Source: Hol, E.M., Pekney, M., 2015. Glial fibrillary acidic protein (GFAP) and the astrocyte intermediate filament system in diseases of the central nervous system. *Current Opinion in Cell Biology*, 32, 121–130.

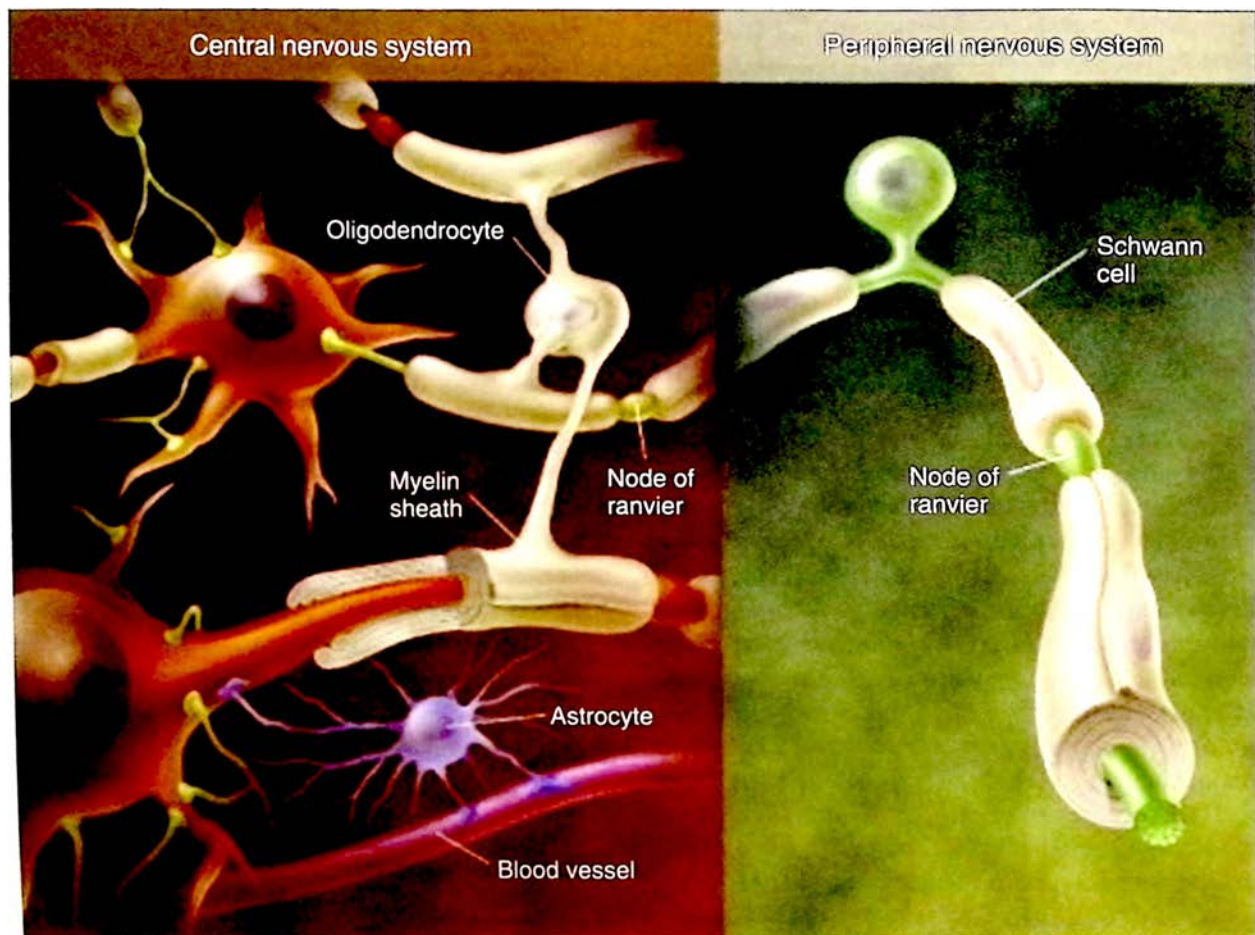


Figure 1.6 Glial cells. Myelinating glia form the electrical insulation on axons that is essential for high-speed transmission of impulses through nerve fibres (axons).

Source: Fields, R.D., 2012. Glial cells. In Ramachandran VS Encyclopedia of human behavior, 2nd edn. Elsevier.

innervate the skeletal muscles and the visceral efferent fibres to the organs, smooth muscles and glands.

The spinal cord has a clearly segmented organisation, which corresponds to the nerve roots attached to it. Posteriorly (dorsally), a continuous series of rootlets containing sensory axons enter the spinal cord. Anteriorly (ventrally), a continuous series of rootlets containing motor axons leave from the spinal cord. These sensory and motor axons merge together to form the spinal nerves, which are a part of the peripheral nervous system (PNS). Lying in

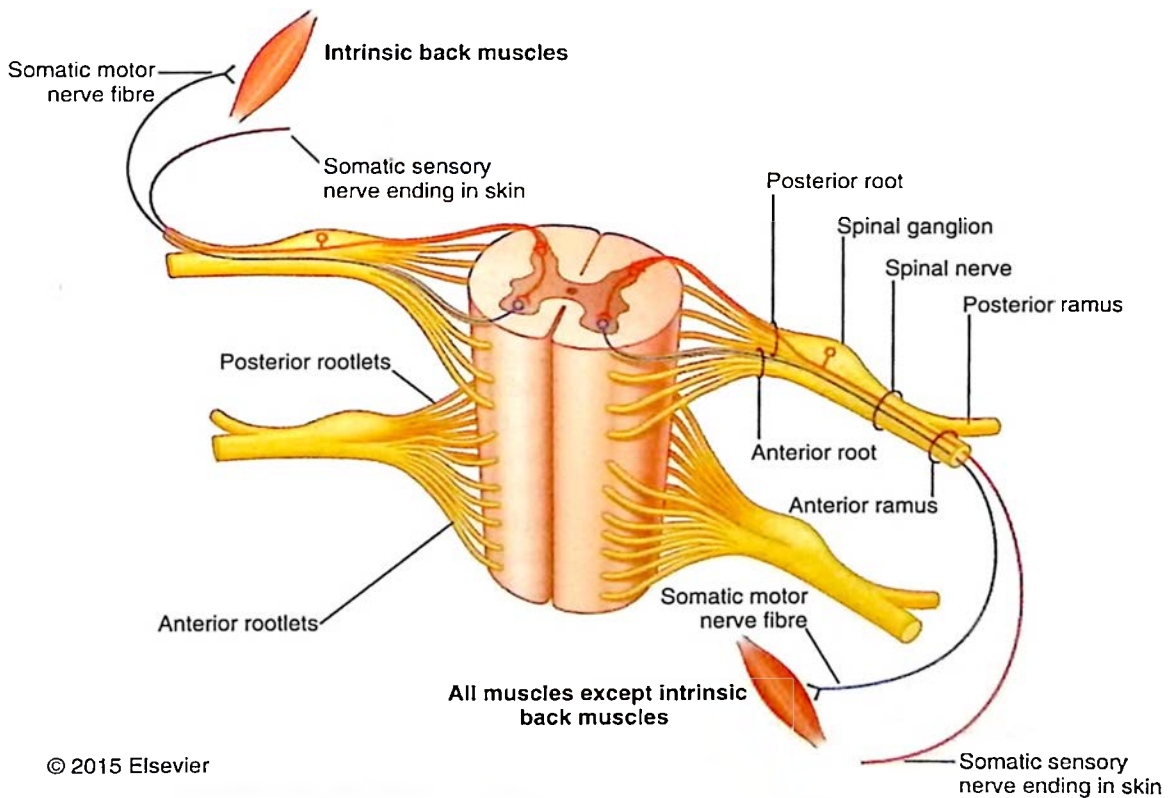
the posterior root is an enlargement, just proximal to the formation of the spinal nerve – the dorsal root ganglion (or spinal ganglion). This contains the cell bodies (soma) of the sensory nerve fibres (the pseudo/unipolar neurons) (Fig. 1.7).

Along the length of the spinal cord are two regional swellings, the cervical enlargement and the lumbosacral enlargement. These represent areas of increased neuron numbers due to the motor supply to the upper limb (cervical enlargement), and lower limb (lumbosacral enlargement). At its caudal end,

the spinal cord is tapered into the conus medullaris and ends in the filum terminale, which is a thickening of the covering meningeal tissues (pia mater) that anchors the spinal cord to the sacral bones of the pelvis. At its rostral end, the spinal cord begins at the level of the foramen magnum of the skull.

The spinal nerves of the PNS emerging from the spinal cord are generally named according to the intervertebral foramina through which they exit. However, the segments of the spinal cord giving rise to these nerves are not at the same level, with most spinal nerves originating more rostrally from the spinal cord than the intervertebral foramina through which they exit. This is due to the differences in growth rate between the tissues of the spinal cord

and vertebrae which take effect from approximately the third month of fetal life. The vertebral column, developed from mesoderm, grows more rapidly than the nervous tissue of the spinal cord, developed from ectoderm. In response to this, the anterior and posterior roots of the lower spinal nerves increase in length as they travel further to exit through the appropriate intervertebral foramen. The lumbosacral nerve roots (represented in blue in Fig. 1.8) are the longest and form the cauda equina of the spinal cord. At birth, the spinal cord therefore terminates at approximately the level of L3, with the adult spinal cord terminating at the L1/L2 level due to similar growth differences in these tissues occurring postnatally.

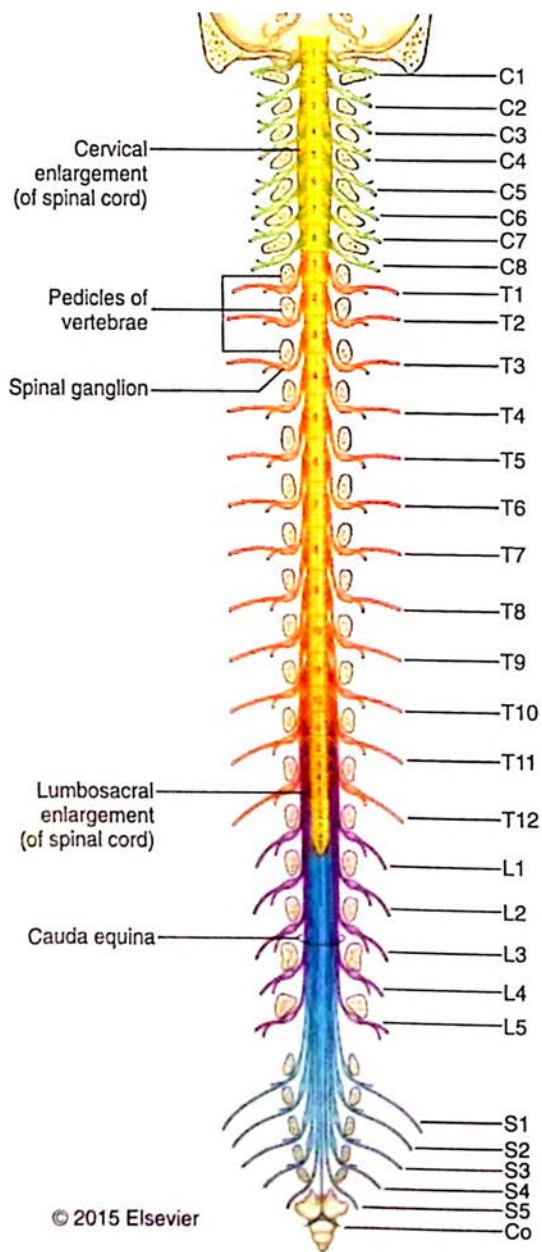


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Figure 1.7 The spinal cord.

Source: Drake, R., Vogel, A.W., et al., 2014. Gray's anatomy for students, 3rd edn. Elsevier.



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Figure 1.8 The spinal cord in situ.

Source: Drake, Vogel, A.W., et al., 2014. *Gray's anatomy for students*, 3rd edn. Elsevier.

Grey and white matter

The spinal cord is marked on its external surface by longitudinal fissures and sulci that are related to the positioning of white matter fibre tracts and the location of entry and exit points for nerve rootlets to the internal grey matter. The external white matter is where the ascending and descending fibre tracts (columns or funiculi) are located. There are three columns of white matter: anterior, posterior and lateral. The internal grey matter is where neurons are located according to their functions, forming motor (ventral), sensory (dorsal) and autonomic (lateral) horns.

The spinal cord has a left and right side, which mirror each other (Fig. 1.9). The left side of the spinal cord receives and sends information from/to the left side of the body and vice versa. Ultimately, whether sensory or motor information travels ipsilaterally or contralaterally within the spinal cord depends upon the type of information being carried and thus the pathway in which it travels. However, all sensory information from the right side of the body is processed at a cortical level in the left hemisphere of the brain and all sensory input from the left side of the body is sent to the right hemisphere of the brain. Similarly, all voluntary motor information sent to produce movement in the right side of the body originates from the cortex of the left hemisphere, and movement in the left side of the body is directed by the cortex of the right hemisphere. The exact details regarding how this takes place and whether the information crosses in the spinal cord or brain stem will be discussed in more detail in the section on sensory systems, which examines the specific pathways (pp. 12–14).

Anteriorly, there is a prominent anterior median fissure that can be seen the whole length of the spinal cord. In this fissure, in the subarachnoid space, sits the anterior spinal artery, which is a major blood supply to the spinal cord. Deep within the fissure and anterior artery sits the anterior white commissure, which is a location for the decussation (crossing from left to right) of a number of sensory and motor fibre paths. Between the anterior median fissure and

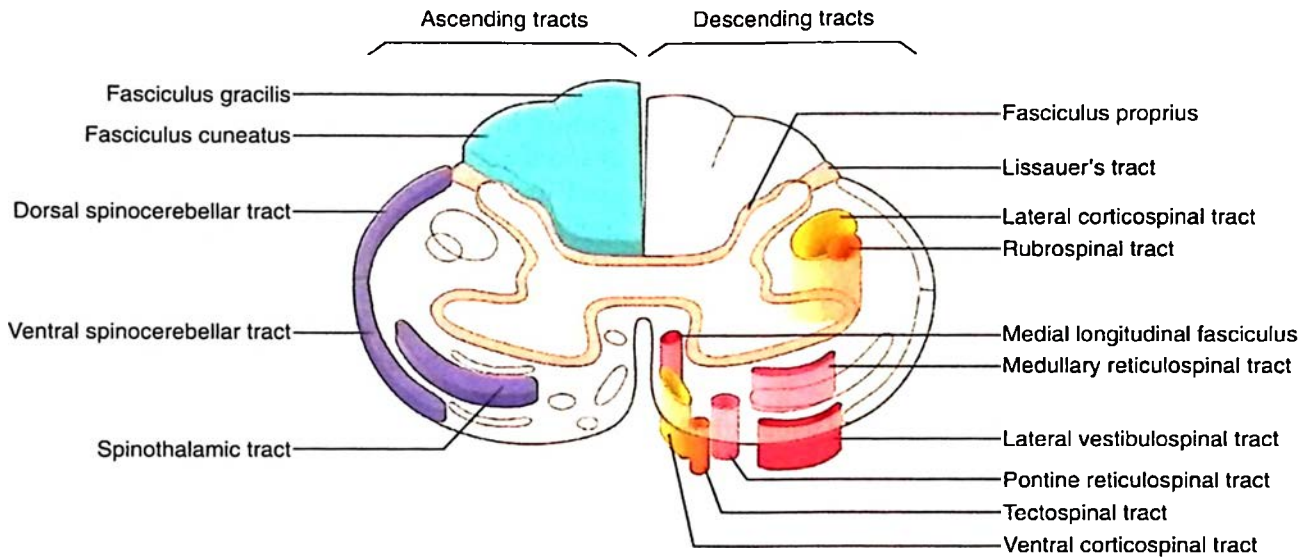


Figure 1.9 Cross-section of spinal cord (demonstrating the grey matter and white matter fibre tracts).

Ascending and descending tracts of the spinal cord. All ascending and descending tracts are present bilaterally. In this image, ascending tracts are emphasised on the left side and descending tracts are emphasised on the right side. In addition, the location of Lissauer's tract and the fasciculus proprius (which contain both ascending and descending fibres) are shown.

Source: Crossman, A., Neary, D., 2015. Neuroanatomy: An illustrated colour text. 5th edn. Churchill Livingstone, Fig. 8.15.

the exit point of the ventral (motor) rootlets sits the anterior column. This column contains a number of ascending and descending fibre tracts, the most prominent of which is the *anterior corticospinal pathway*.

Posteriorly, a posterior median sulcus can be identified on the external surface of the spinal cord. Sitting on both the left and the right sides of the spinal cord, between the posterior median sulcus and the entry point of the dorsal (sensory) rootlets, lies the posterior column. This column contains the large sensory fibre tracts of the *dorsal column–medial lemniscus (DCML) pathway*. In the upper part of the spinal cord (the cervical and upper thoracic regions), this column contains two tracts (or fasciculi): the *fasciculus gracilis* (medially) and the *fasciculus cuneatus* (laterally). These carry somatic sensory information from the lower trunk and limbs and the upper trunk and limbs, respectively.

Therefore, in the lower spinal cord only the fasciculus gracilis is present. The sensory information carried by these fibre tracts to the brainstem includes fine (discriminative) touch, vibration and proprioception from muscles and joints.

Laterally, sitting between the ventral (motor) and dorsal (sensory) rootlets of the spinal cord, lies the lateral column. This is the largest white matter column of the spinal cord and contains both ascending and descending fibre tracts, including the *spinocerebellar* (sensory), *spinothalamic* (sensory) and the *lateral corticospinal* (motor) pathways.

The clinical presentation of spinal cord injuries (SCI) is dependent upon the severity and location of injury, since the long white matter tracts of the spinal cord are arranged somatotopically as they interconnect the brain with the autonomic and peripheral nervous systems.

SPINAL CORD: SYSTEMS

The spinal cord functions both as a conduit for tracts that send information to and from the higher centres in the brain and as a processing centre for intrinsic functions, such as muscle tone and reflexes. These two functions are structurally separated, with the tracts being located in the peripheral white matter of the spinal cord and the central grey matter containing spinal neurons.

Somatic system

There are 31 pairs of spinal nerves emanating from the spinal cord. Each spinal nerve carries a combination of somatic sensory and somatic motor information, as well as visceral sensory and visceral motor information.

Each segment of the spinal cord and associated spinal nerve supplies a specific area of the skin, forming a *dermatome*. There is overlap between dermatome areas, yet they can be identified on a dermatome map, which is useful clinically for identifying where there has been damage to the spinal cord. Similarly, the anterior spinal roots and the associated segment of the spinal cord provide motor control to a predetermined group of muscle fibres, which forms a *myotome*. Each skeletal (somatic) muscle of body is innervated by several spinal nerves and this is represented on a myotome map. Thus, a myotome map provides information about the types of movements that will be affected by damage to the spinal cord and/or spinal nerves (Fig. 1.10).

Sensory systems

There are three sensory (ascending) pathways in the spinal cord: the dorsal column, the spinothalamic and the spinocerebellar pathways. All of these pathways carry inputs from the somatic (body) tissues, relating to the sensory modalities of touch, pain, temperature and proprioception (Fig. 1.11).

Sensory neurons are structured to have their dendrites associated with specialised receptors that respond to specific stimuli. This information is then carried into the CNS and the spinal cord through

the sensory component of the spinal nerve. Sensory neurons have their soma (cell bodies) located in the ganglion of the dorsal root and they send sensory information into the CNS for processing at specific sensory nuclei located in either the spinal cord itself or the brainstem. Sensory neurons are grouped together in the spinal cord into pathways (tracts) that carry specific sensory modalities into the CNS.

The largest sensory pathway of the spinal cord is the dorsal column–medial lemniscus (DCML) pathway. This pathway detects and carries information relating to touch and mechanical stimuli (i.e. discriminative touch, pressure, vibration and proprioception). In the spinal cord this pathway provides input to spinal reflex arcs and contributes to further input processing within the dorsal horn. However, the majority of inputs form the posterior column of spinal cord white matter, composed of two tracts (or fasciculi): the *fasciculus gracilis* (medially) and the *fasciculus cuneatus* (laterally). Information travelling in this sensory pathway is carried ipsilaterally within the spinal cord, only crossing to the opposite side of the CNS after synapsing in the medulla oblongata at the nucleus gracilis or nucleus cuneatus. This information is then processed by the sensory centres of the brain.

In the lateral white matter column of the spinal cord are two more sensory (ascending) spinal pathways: the spinothalamic pathway (also referred to as the anterolateral pathway) and the spinocerebellar pathway. The *spinothalamic pathway* detects and carries information relating to non-discriminative touch, pain and temperature. This information is sent to the thalamus and therefore this pathway is vital in mediating conscious awareness of pain and temperature. Within the spinal cord, fibres carrying spinothalamic information travel only a short distance before synapsing in the superficial laminae or in the nucleus proprius of the dorsal horn. Following this, fibres are carried in the white matter of the spinal cord on the opposite side (contralateral) to the origin of the input (i.e. pain and temperature from the left side of the body is carried in the right

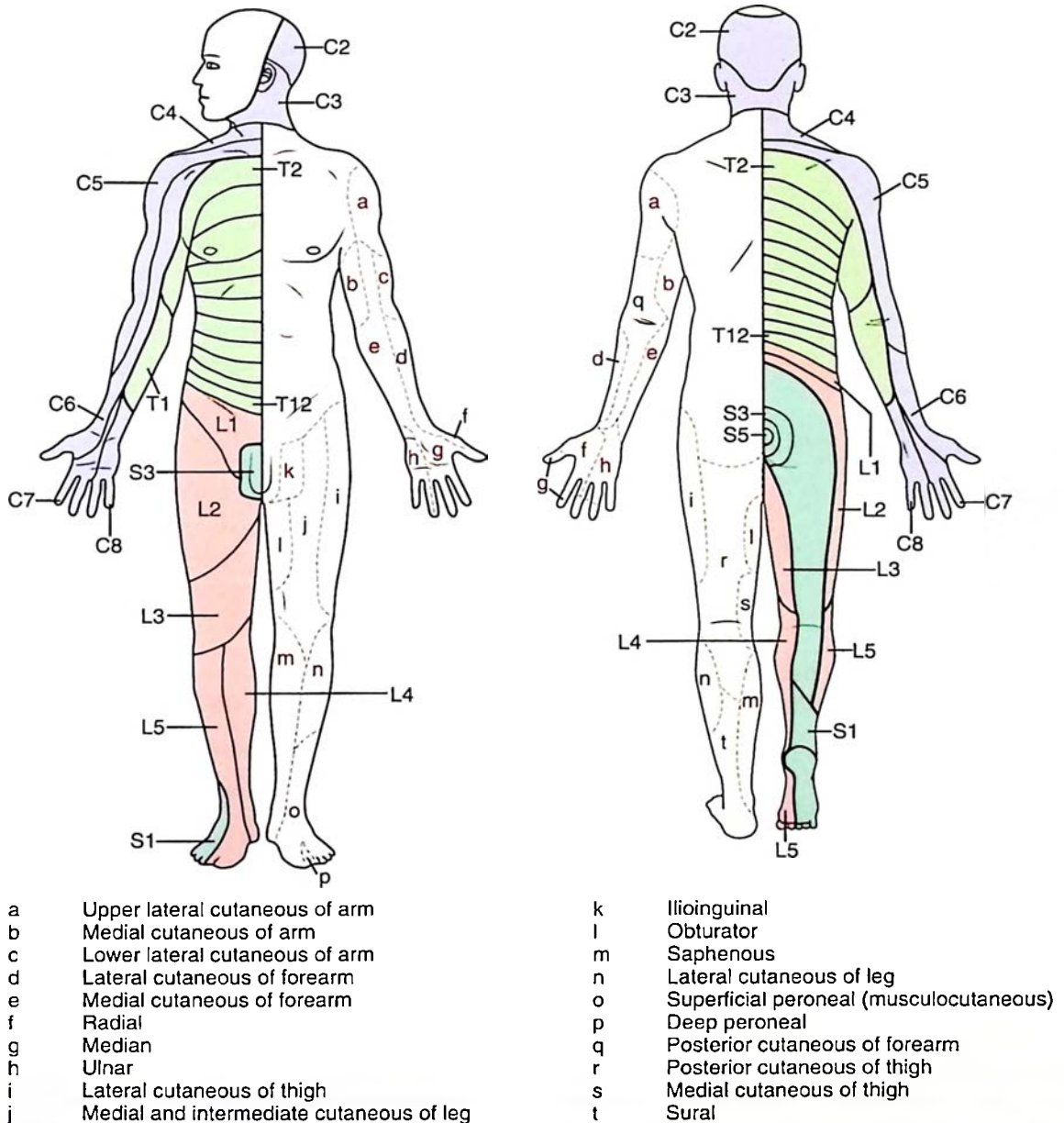


Figure 1.10 Dermatome and myotome maps.

Source: Crossman, A., Neary D., 2015. Neuroanatomy: An illustrated colour text, 5th edn. Churchill Livingstone. Fig 3.14, p. 43.

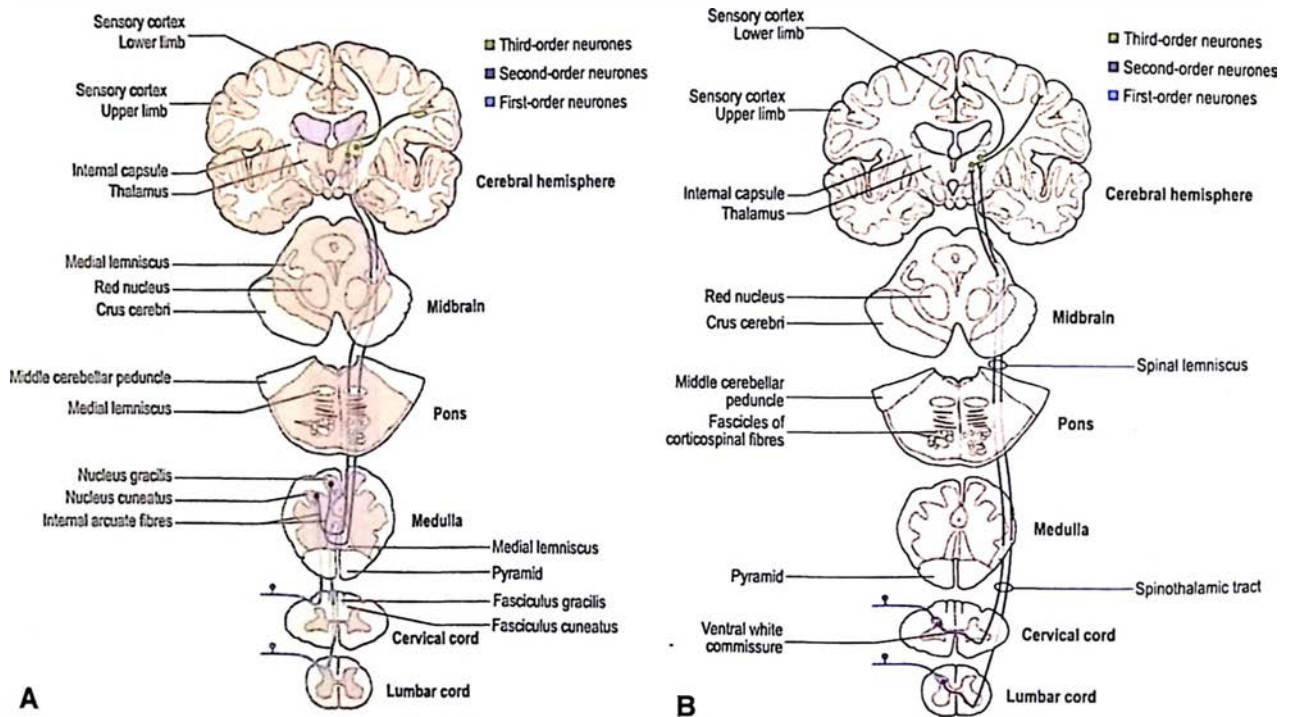


Figure 1.11 A, B ascending pathways.

Source: Crossman, A., Neary, D. 2015. *Neuroanatomy: An illustrated colour text*, 5th edn. Churchill Livingstone. Figs 8.16, 8.17.

side of the spinal cord). This information is then taken to the sensory centres of the brain (Fig. 1.12).

The spinocerebellar pathway detects and carries proprioceptive information from the limbs to the cerebellum. This is achieved through the integration of multiple sensory modalities, including proprioceptive information from joints, muscles and tendons and information from skin receptors which sense movement of the body. Once this information enters the spinal cord through the dorsal root there are a number of tracts that direct these sensations to the cerebellum, all of which contribute to the spinocerebellar pathway. In this way, the spinocerebellar pathway not only provides input to the cerebellum regarding body positioning, it also contributes important information for the

fine-tuning and adjustment of ongoing movements that facilitate motor learning. The tracts that make up the spinocerebellar pathway include the posterior spinocerebellar tract, the anterior spinocerebellar tract, the cuneocerebellar tract and the rostral spinocerebellar tract. The posterior spinocerebellar, rostral spinocerebellar and cuneocerebellar tracts all carry proprioceptive information ipsilaterally within the spinal cord, and the anterior spinocerebellar tract carries proprioceptive information contralaterally within the spinal cord. This pathway does not take this proprioceptive information to the sensory centres of the brain.

The typical clinical presentations that reflect the implications associated with damage of the pathways are discussed in Chapter 11.

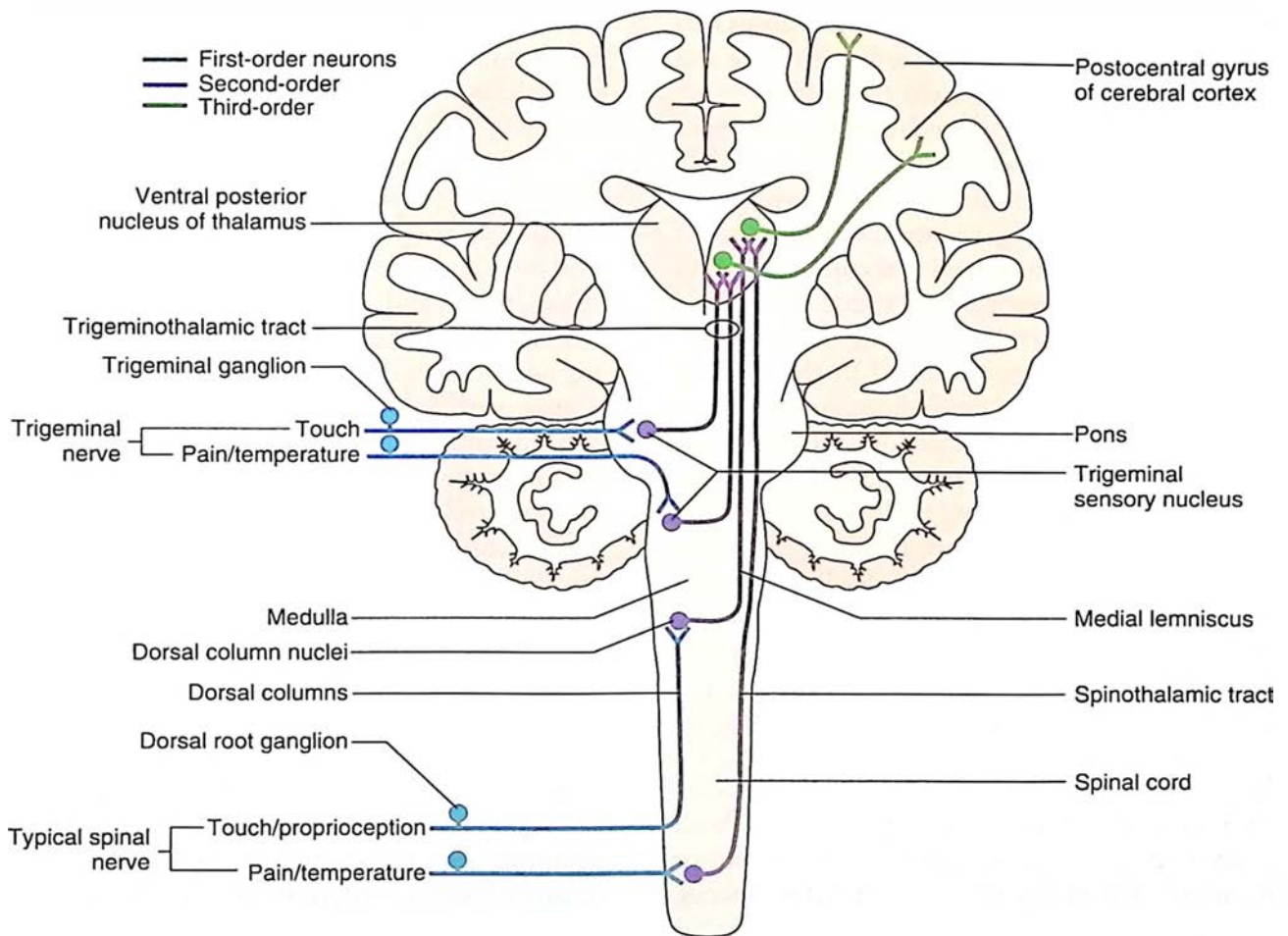


Figure 1.12 Sensory pathways

Source: Crossman, A., Neary D. 2015. *Neuroanatomy: An illustrated colour text*, 5th edn. Churchill Livingstone. Fig 1.28, p. 20.

Motor systems

Human movement is generated by the combined activity of multiple neuronal circuits that collect, integrate and feed back neural information to produce precisely timed and sequenced skeletal muscle contractions. Research over many years has demonstrated that the motor control system consists of multiple, interconnected levels of organisation, often referred to as hierarchical levels. Together, these levels of motor control are able to produce a vast array of movements, ranging from repetitive

routine movements, such as walking, to more specialised movements as, for example, playing a musical instrument.

In all movements there are three main component systems that must interconnect to produce the desired output, whether it be a simple reflex or a sophisticated movement pattern. However, the input of each of these systems can be varied, which gives rise to the diversity and range of movements possible.

The first motor system involves neurons confined to the spinal cord, which are essential for producing rhythmic and patterned motor activity.¹⁵ This system

includes the diverse range of spinal interneurons that interconnect within the spinal cord to produce and support activities for movement execution.

The second motor system involves interconnections between the local spinal circuits and higher CNS centres in the brainstem and cerebral cortex. This includes many ascending and descending pathways (Fig. 1.13), allowing bi-directional communication and interaction between the local spinal circuits and the higher CNS control and command centres.¹⁶ These supraspinal centres (located in the cerebral cortex, basal ganglia and cerebellum, among other locations) are involved in selection, initiation and activation of motor action programs.

Lastly, there are the sensory feedback systems that constantly monitor the consequences of motor action and initiate adjustments.¹⁷ Sensory feedback circuits provide important input to the spinal cord relating to external inputs and from specific body regions (i.e. proprioception is somatotopically processed) and thus contribute to the coordinating and sequencing of motor outputs.

These three separate and yet highly interconnected systems of motor control are responsible for both the diversity and the specificity seen in motor behaviour.¹⁸ The ability of these systems to operate

individually and collectively, depending upon the task, create a huge challenge in the understanding of the connectivity and functions of the motor system.

Spinal cord neurons

Research on the physiological characteristics of spinal cord neurons, their functional output and their role in generating and regulating movement, has been evolving for more than a century. Unfortunately, there are significantly different profiles of activity from neurons within the spinal cord across different species of mammals, which has added to this challenge. The human motor systems of the CNS (both within the brain and within the spinal cord), are among the most complex of all species both structurally and functionally. The human brain has significant regions of cortex involved in the decision-making, planning and patterning for movement, and humans are capable of very precise, controlled and coordinated movements as a result of this system.

The motor cortex, along with other brain areas such as the midbrain, hindbrain, cerebellum and basal ganglia, are involved in decision-making and planning for movement initiation. However, the quality of movement produced relies heavily on the

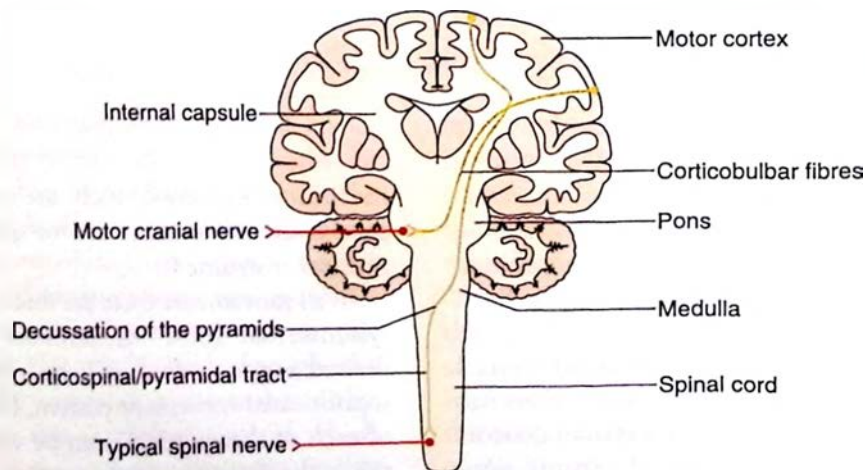


Figure 1.13 Motor pathways

Source: Crossman, A., Neary D., 2015. *Neuroanatomy: An illustrated colour text*, 5th edn. Churchill Livingstone. Fig 1.29, p. 21.

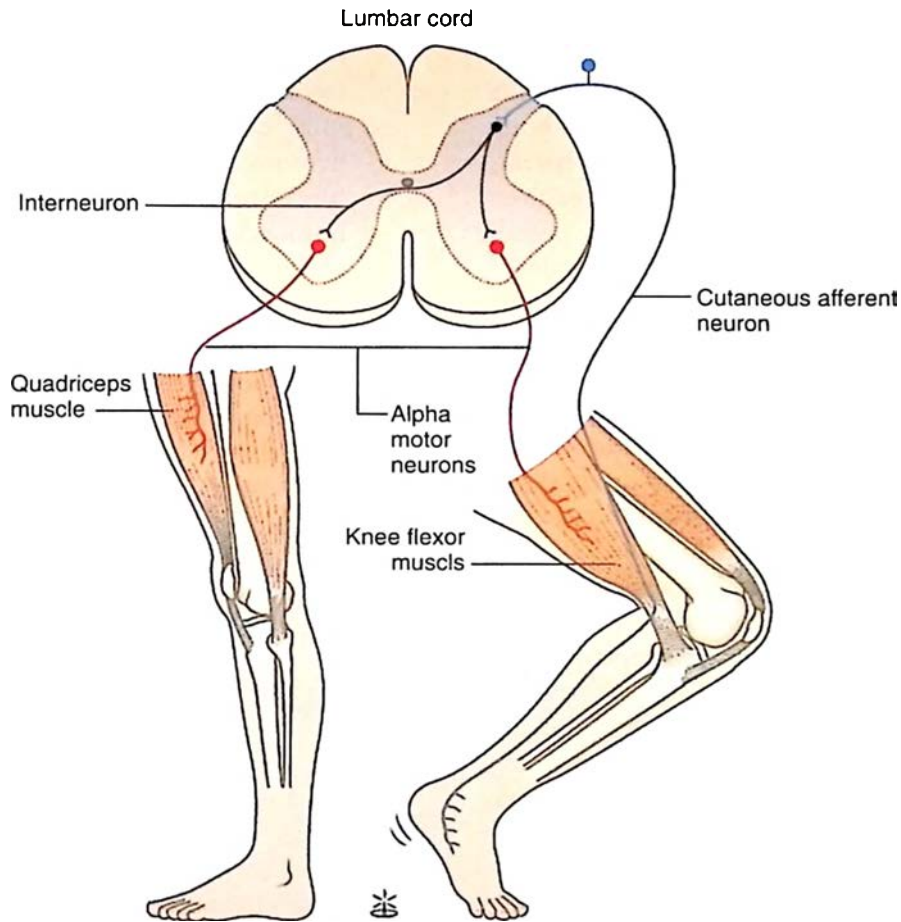


Figure 1.14 An example of motor neurons and interneurons of the spinal cord grey matter.

Source: Crossman, A., Neary, D., 2015. Neuroanatomy: An illustrated colour text, 5th edn. Churchill Livingstone. Fig. 8.14.

translation of descending inputs and the feedback from the periphery by spinal motoneurons (such as the γ motor neurons) and interneurons that form multiple spinal neural networks.

Motor neurons

Motor neurons whose cell bodies are located in the cortex of the brain are referred to as upper motor neurons (UMNs), and those motor neurons whose cell bodies are located in the spinal cord are termed lower motor neurons (LMNs). LMNs for the somatic (skeletal) motor system are located in the ventral (anterior) horn of the spinal cord grey matter, as

are a number of regulatory and modulatory motor interneurons (Fig. 1.14).

α -motor neurons are large multipolar neurons that directly innervate skeletal muscle fibres. The α -motor neuron and the muscle fibres it innervates are together referred to as the **motor unit**. When the α -motor neuron is activated, those fibres it supplies will contract. There are many different sized motor units throughout the human body, allowing different muscles and body regions to display varying degrees of movement strength, control and dexterity. The powerful postural muscles of the body motor units are large, allowing strong muscle contractions to